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Effect of MFD viscosity on ferroconvection in a fluid saturated porous medium with variable gravity

Convective instability of a horizontal ferromagnetic fluid saturated porous layer with magnetic field dependent (MFD) viscosity subjected to gravity field varying with distance in the layer is investigated. The fluid motion is described by the Brinkman model. The method of small perturbation is applied and the resulting eigenvalue problem is solved using the higher order Galerkin technique. The stationary instability is shown to be the preferred mode of instability and the resulting eigenvalue problem is solved by taking into account the realistic rigid-rigid-isothermal boundary conditions. The study reveals that the effect of MFD viscosity is to delay the onset of ferroconvection and the stabilizing effect of MFD viscosity is reduced when the magnetic Rayleigh number is sufficiently large. In the presence of variable gravity, the effect of magnetic and non-magnetic parameters on ferroconvective instability is also discussed.

Keywords: Ferrofluid, MFD viscosity, porous media, magnetic field, variable gravity

1.0 Introduction

Ferromagnetic fluid is a liquid that can be described as a colloidal system of sufficiently small mono-domain magnetic particles dispersed in various carrier liquids. These fluids behave as homogeneous continuums, exhibiting a variety of fascinating phenomena. These particles are coated with a stabilizing dispersing agent known as a surfactant, which prevents particle agglomeration even when the ferromagnetic fluid is subjected to a strong magnetic field gradient. The resulting material behaves similarly to a normal fluid, with the exception that it can experience forces due to magnetic polarization. Ferromagnetic fluids do not exist in nature and must be created artificially. These fluids have a wide range of applications, including novel energy conversion devices, levitation devices, and rotating seals, lubrication, printing, MRI (Magnetic Resonance Imaging), vacuum technology, vibration dumping, metal recovery and medicine. The convective instability of a ferromagnetic fluid for a fluid layer heated from below in the presence of uniform vertical magnetic field has been considered by (Finlayson, 1970). (Gupta, 1979) studied thermal instability in a ferromagnetic fluid layer is subject to Coriolis force and saturated by a vertical magnetic field, over stability cannot occur if the Prandtl number is greater than unity. (Yamada, 1982) have generalized the boundary conditions on the magnetic scalar potential and have presented calculations for ferrofluids confined between plates of infinite magnetic permeability. Stiles and Kagan, 1990 probed the thermoconvective instability of a horizontal ferrofluid layer in a strong vertical magnetic field. Their findings also called into question the claimed satisfactory agreement between the experiments and Finlayson's theoretical model, which they generalized. Abraham, 2002 performed an analytical analysis of ferroconvection with micropolar characteristics, demonstrating that magnetic fluids with micropolar characteristics are invariably more stable than their Newtonian counterparts. Kaloni and Lou, 2004 consider the convective instability problems in the horizontal layer of a magnetic fluid with a Brownian relaxation mechanism.

A medium which is solid body containing pores is called a porous medium. Extremely small void spaces in a solid are called molecular interstices, and very large ones are called caverns. Pores are void spaces intermediate in size between caverns and molecular interstices. Flow of fluid is possible only if at least part of pore space is interconnected. The interconnected part of pore system is called effective pore space of the porous medium. The porous medium of moderately large permeability necessitates the use of the Brinkman's model and medium of very low permeability allows us to use Darcy's model. Porous medium is classified as unconsolidated or consolidated and as ordered or random. Examples of unconsolidated media are beach sand, glass beads, catalyst pellets, soil, gravel etc. Examples of consolidated media are most of the naturally occurring rocks such as sandstone, limestone and so forth. In addition, concrete, cement, bricks, paper, cloth etc., are man-made consolidated media. In a natural porous medium the distribution of pores with respect to shape and size is

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irregular. Examples of natural porous media are beach sand, sandstone, limestone, rye bread and wood etc.

The breakdown of stability of a fluid layer subjected to a vertical temperature gradient in a porous medium, as well as the possibility of convective flow is investigated by Wooding, 1960. The relationship between chemical processes and natural convection in porous media is numerically examined by Shorter, 1983. Thermoconvective instability in a ferromagnetic fluid saturating a porous medium subjected to a vertical magnetic field has been analyzed using Brinkman model by Vaidyanathan et al., 1991. The influence of rotation on the initiation of convection in a horizontal layer of ferrofluids spinning about its vertical axis, heated from below and with a uniform surface. Linear instability analysis is used to investigate the vertical magnetic field by Venkatasubramanian and Kaloni, 1994. The effects of magnetization, a stable solute gradient, and MFD viscosity on the onset of convection were examined by (Sunil et al., 2005. Nanjundappa et al., 2010 investigate numerically the conditions for the onset of ferroconvection in a high permeability ferromagnetic fluid saturated porous layer by employing a non Darcian model for rigid-rigid paramagnetic and rigid free paramagnetic boundaries with fixed heat flux and convective-radiative exchange conditions at the lower and upper boundaries, respectively. In a ferrofluid saturating a porous medium, Hemalatha, 2014 includes the influence of a magnetic field dependent viscosity, the Coriolis force, and the Soret effect. A linear stability analysis has been performed. The Brinkman model is employed. Ram et al., 2019 studied the impact of magnetic field dependent viscosity on thermal convection in a ferrofluid layer heated from below in the presence of dust particles and subjected to a uniform vertical magnetic field. Prakash et al., 2020 used the Darcy Brinkman model to examine the effect of magnetic field dependent viscosity on thermal convection in a rotating ferrofluid layer heated from below saturating a porous medium in the presence of a uniform vertical magnetic field.

Although the Earth's gravity field changes with height above its surface, we normally ignore this variation in the lab and treat the field as a constant. For large-scale flows in the ocean, atmosphere, or mantle, however, this may not be the case. It is consequently necessary to think of gravity as a variable quantity that varies with distance from the center.

Pradhan and Samal, 1987 point out, it is likely to be important to consider variable gravity effects in the large-scale convection of (planetary) atmospheres. The thermal stability of a nonviscous fluid layer and that of a viscous fluid layer, subject to a gravitational field varying with distance in the layer, have been analyzed by Straughan, 1989. In an anisotropic porous media; Sharma et al., 2001 investigated the influence of a changing gravitational field on convective instability generated by an internal heat source and an inclination temperature gradient. Rana and Kumar, 2010 studied the thermal instability of the Rivlin–Ericksen elasto-viscous rotating fluid that permeates with suspended particles in a porous material under a fluctuating gravity field. Rana, 2013 examined the thermosolutal convection in Walters' (Model) elastico-viscous rotating fluid permeated with suspended particles and variable field in hydromagnetic in a porous medium. Bala and Chand, 2015 study the variable gravity effects on the thermal instability of a ferromagnetic fluid in a Brinkman-Darcy porous medium by the Galerkin residual weighted method. Mahajan and Sharma, 2018 used the Chebyshev pseudospectral method to find numerical solutions for rigid–rigid, rigid–free, and free–free boundary conditions in water and ester-based magnetic nano-fluids and discussed the results. Pundir et al., 2021 planned to examine the effect of rotation and a magnetic field on the thermosolutal instability of a ferromagnetic fluid in the presence of a variable gravity field. Sudhir Kumar Pundir et al., 2021 discussed the effect of Hall current on the thermal instability of couple-stress ferromagnetic fluid in the presence of a variable gravity field and a horizontal magnetic field saturated in a porous medium.

In this paper an attempt is made to study the effect of variable viscosity on the convective instability of a fluid saturated a porous medium subject to gravitational filed. Various cases of stabilizing and destabilizing effects on temperature are analyzed using Darcy-Brinkman models. The results are illustrated graphically.

2.0 Mathematical formulation

We consider a ferromagnetic fluid saturated packed porous layer confined between two infinite horizontal surfaces $z = \frac{d}{2}$ and $z = -\frac{d}{2}$ under the influence of a uniform, vertical magnetic field H_0 and a time periodically varying gravity force g=(0, 0,–g) acting on it, where $g = -g_0\left(1+\eta z\right)\hat{k}$ with g_0 being the mean gravity.

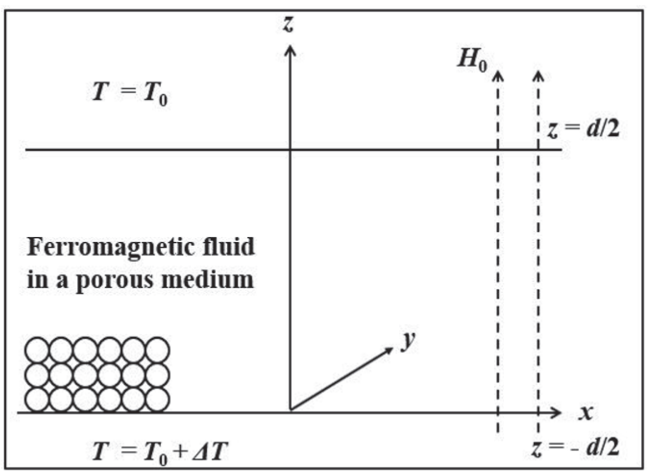

Fig.1: Schematic of the problem

The Boussinesq approximation is involved to account for the effect of density variation. It is assumed that the fluid and solid matrix are in local thermal equilibrium. The governing equations describing flow in an incompressible, non-conducting magnetic fluid saturated porous layer are (Maruthamanikandan [25]).

$$\nabla \cdot \vec{q} = 0$$

$$\rho_0 \left[\frac{1}{\varepsilon_p} \frac{\partial \vec{q}}{\partial t} + \frac{1}{\varepsilon_p^2} (\vec{q} \cdot \nabla) \vec{q} \right] = -\nabla p \quad \text{... (1)}$$

$$+ \rho \vec{g} - \frac{\mu_f}{K} \vec{q} + \nabla \cdot \left[\bar{\mu}_f \left(\nabla \vec{q} + \nabla \vec{q}^{Tr} \right) \right] + \nabla \cdot \left(\vec{H} \vec{B} \right) \quad \text{... (2)}$$

$$\varepsilon \left[\rho_0 \bar{C}_{V,H} - \mu_0 \vec{H} \cdot \left(\frac{\partial \vec{M}}{\partial T} \right)_{V,H} \right] \left[\frac{\partial T}{\partial t} + (\vec{q} \cdot \nabla) T \right] + \mu_0 T \left(\frac{\partial \vec{M}}{\partial T} \right)_{V,H} \cdot \left[\frac{\partial \vec{H}}{\partial t} + (\vec{q} \cdot \nabla) \vec{H} \right] \quad \text{... (3)}$$

$$+ (1-\varepsilon)(\rho_0 C)_s \frac{\partial T}{\partial t} = K_1 \nabla^2 T$$

$$\rho = \rho_0 \left[1 - \alpha (T - T_a) \right] \quad \text{... (4)}$$

$$\vec{M} = \frac{\vec{H}}{H} M(H, T) \quad \text{... (5)}$$

$$M = M_0 + \chi_m (H - H_0) - K_m (T - T_a) \quad \text{... (6)}$$

where $\vec{q}=(u, v, w)$ is the fluid velocity, ρ_0 is the reference density, ε is the porosity, t is the time, p is the pressure, $\vec{g}$ is the acceleration due to gravity, ρ is the fluid density, μ_f is the dynamic viscosity, $\bar{\mu}_f$ is the effective viscosity, κ is the permeability of the porous medium, $\vec{H}$ is the magnetic field, $\vec{B}$ is the magnetic induction, T is the temperature, μ_0 is the magnetic permeability, $\vec{M}$ is the magnetization, K_1 is the thermal conductivity, α is the thermal expansion coefficient, $C_{V,H}$ is the specific heat at constant volume and magnetic field, χ is the magnetic susceptibility, K is the pyromagnetic coefficient and Tr denotes the transpose.

The relevant maxwell equations are

$$\nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{H} = 0, \quad \vec{B} = \mu_0 \left(\vec{H} + \vec{M} \right) \quad \text{... (7)}$$

The fluid viscosity is taken to be magnetic field dependent viscosity in the following forms

$$\mu_f(H) = \frac{\mu_1}{1 - \delta(H - H_0)}, \qquad \bar{\mu}_f(H) = \frac{\mu_2}{1 - \delta(H - H_0)} \quad \text{... (8)}$$

where μ_1 and μ_2 are values of μ_f and $\bar{\mu}_f$ at $T=T_a$ and $0 < \delta < 1$.

Equations characterizing the basic state are introduced in the form

$$\left.\begin{aligned} &\frac{\partial}{\partial t} = 0; \vec{q} = \vec{q}_b(z) = 0; \\ &T = T_b(z); p = p_b(z); \\ &\rho = \rho_b(z); \vec{H} = H_b(z); \\ &\vec{M} = M_b(z); \vec{B} = B_b(z); \\ &\mu_f = \mu_{f_b}(z), \bar{\mu}_f = \bar{\mu}_{fb}(z) \end{aligned}\right\} \quad \text{... (9)}$$

The solution pertaining to the basic state reads

$$\rho_b = \rho_0 \left[1 + \alpha(z) \right] \quad \text{... (10)}$$

$$\vec{H}_b = \left[H_0 - \frac{K \beta z}{1+\chi} \right] \hat{k} \quad \text{... (11)}$$

$$\vec{M}_b = \left[M_0 + \frac{K \beta z}{1+\chi} \right] \hat{k} \quad \text{... (12)}$$

$$\vec{B} = \mu_0 \left(\vec{H} + \vec{M} \right) \hat{k} \quad \text{... (13)}$$

$$\mu_{f_b}(H) = \frac{\mu_1}{1 + \dfrac{\delta K \beta z}{1+\chi}} \quad \text{... (14)}$$

$$\bar{\mu}_{f_b}(H) = \frac{\mu_2}{1 + \dfrac{\delta K \beta z}{1+\chi}} \quad \text{... (15)}$$

3.0 Linear stability analysis

The perturbed state equations involving infinitesimally small perturbations are

$$\left.\begin{aligned} &\vec{q} = \vec{q}_b + \vec{q}' = (u', v', w'), p = p_b + p', \\ &T = T_b + T', \rho = \rho_b + \rho' \\ &\mu_f = \mu_{f_b} + \mu'_f, \bar{\mu}_f = \bar{\mu}_{f_b} + \bar{\mu}'_f, \\ &\vec{M} = \vec{M}_b + \vec{M}', \phi = \phi_b + \phi', \\ &\vec{H} = \vec{H}_b + \vec{H}', \vec{Q} = \vec{Q}_b + \vec{Q}' \end{aligned}\right\} \quad \text{... (16)}$$

where the perturbed quantities are indicated by the primes. The linearized equations governing small perturbations therefore take the from

$$\begin{aligned} \rho_0 \frac{\partial}{\partial t} \left(\nabla^2 w' \right) &= \alpha \rho_0 g_0 (1 + \eta z) T' - \frac{\mu_{fb}}{k} \nabla^2 w' \\ &+ \frac{\mu_0 K^2 \beta}{1+\chi} \nabla_1^2 T' - \mu_0 K \beta \frac{\partial}{\partial z} \left(\nabla_1^2 \phi' \right) \\ &- \frac{\partial^2 \bar{\mu}_{fb}}{\partial z^2} \left(\nabla_1^2 w' - \frac{\partial^2 w'}{\partial z^2} \right) \\ &+ 2 \frac{\partial \bar{\mu}_{fb}}{\partial z} \frac{\partial}{\partial z} \left(\nabla^2 w' \right) + \bar{\mu}_{fb} \nabla^4 w' \end{aligned} \quad \text{... (17)}$$

$$\begin{bmatrix} (\rho_{0C})_1 \dfrac{\partial T'}{\partial t} \\ -\mu_0 K T_a \dfrac{\partial}{\partial t} \left(\dfrac{\partial \phi'}{\partial z} \right) \end{bmatrix} = k_1 \nabla^2 T' + \left[(\rho_0 c)_2 - \frac{\mu_0 K^2 T_a}{1+\chi} \right] \beta w' \quad \text{... (18)}$$

$$\left(1+\frac{M_0}{H_0}\right)\nabla_1^2\phi'+(1+\chi)\frac{\partial^2\phi'}{\partial z^2}-K\frac{\partial T'}{\partial z}=0 \quad \text{... (19)}$$

where,

$(\rho_0 C)_1=\varepsilon\rho_0 C_{V,H}+\varepsilon\mu_0 K H_0+(1-\varepsilon)(\rho_0 C)_s$

$(\rho_0 C)_2=\varepsilon\rho_0 C_{V,H}+\varepsilon\mu_0 K H_0$, with ϕ' being the magnetic potential.

The normal mode solution is adopted and the same has the form

$$\begin{bmatrix} W' \\ T' \\ \phi' \end{bmatrix}=\begin{bmatrix} W(z) \\ \theta(z) \\ \phi(z) \end{bmatrix}e^{i(lx+my)+\sigma t} \quad \text{... (20)}$$

where l and m are respectively the wave numbers in x and y directions and σ is the growth rate. Substitution of equation (15) into (12) - (14) leads to

$$\begin{aligned}&\rho_0\sigma\left(D^2-k_h^2\right)W\\ &=-\alpha\rho_0 g(1+\eta z)k_h^2\theta-\frac{\mu_{f_b}}{k}\left(D^2-k_h^2\right)W\\ &+\frac{\mu_0 K^2\beta}{1+\chi}k_h^2\theta+\mu_0 K\beta k_h^2 D\phi\\ &+D^2\mu_{f_b}\left(D^2+k_h^2\right)W\\ &+2D\bar{\mu}_{f_b}\left(D^2-k_h^2\right)DW\\ &+\bar{\mu}_{f_b}\left(D^2-k_h^2\right)^2 W\end{aligned} \quad \text{... (21)}$$

$$\begin{bmatrix}(\rho_0 C)_1\sigma\theta\\ -\mu_0 K T_a\sigma D\phi\end{bmatrix}=k_1\left(D^2-k_h^2\right)\theta-\left[(\rho_0 C)_2-\frac{\mu_0 K^2 T_a}{1+\chi}\right]\beta W \quad \text{... (22)}$$

$$(1+\chi)D^2\phi-\left(1+\frac{M_0}{H_0}\right)k_h^2\phi-KD\theta=0 \quad \text{... (23)}$$

where $D=\frac{d}{dz}$ and $k_h^2=l^2+m^2$ is the overall horizontal wave number. Non-dimensionalizing equations (16)-(18) using the scaling

$$\left.\begin{aligned}&z*=\left(\frac{z}{d}\right);a=\kappa_h d;w*=\frac{wd}{k};\\ &\theta*=\frac{\theta}{\beta d};\phi*=\frac{\phi}{\frac{K\beta d^2}{1+\chi}};\sigma*=\frac{\sigma}{\frac{k}{d^2}};\end{aligned}\right\} \quad \text{... (24)}$$

$$\begin{aligned}&\frac{\sigma}{P_r}\left(D^2-a^2\right)W\\ &=-R(1+\eta z)a^2\theta-Da^{-1}g(z)\left(D^2-a^2\right)W\\ &-Na^2\theta+Na^2D\phi+2\Lambda V^2g^3(z)\left(D^2+a^2\right)W\\ &-2\Lambda Vg^2(z)\left(D^2-a^2\right)DW\\ &+\Lambda g(z)\left(D^2-a^2\right)^2W\end{aligned} \quad \text{... (25)}$$

$$\lambda\sigma\theta=\left(D^2-a^2\right)\theta+W \quad \text{... (26)}$$

$$\left(D^2-M_3a^2\right)\phi-D\phi=0 \quad \text{... (27)}$$

Where $\Pr=\frac{\mu_1}{\rho_0\kappa}$ is the Prandtl number, $Da^{-1}=\frac{d^2}{k}$ is inverse Darcy number, $\Lambda=\frac{\mu_2}{\mu_1}$ is Brinkman number, $R=\frac{\alpha\rho_0 g\beta d^4}{\mu_1\kappa}$ is the Rayleigh number, $N=\frac{\mu_0K^2\beta^2d^4}{\mu_1\kappa(1+\chi)}$ is magnetic Rayleigh number, $V=\frac{\delta K\beta d}{1+\chi}$ is the variable viscosity parameter and $g(z)=\frac{1}{1+Vz}$. The appropriate boundary conditions are (Finlayson, 1970)

$$\left.\begin{aligned}&W=DW=\theta=0\ \ at\ z=\pm\frac{1}{2}\\ &D\phi+\frac{a\phi}{1+\chi}=0\ \ at\ \ z=\frac{1}{2},\\ &D\phi-\frac{a\phi}{1+\chi}=0\ \ at\ z=-\frac{1}{2}\end{aligned}\right\} \quad \text{... (28)}$$

It can be shown that no unstable oscillatory longitudinal mode is possible and that the critical Rayleigh number for the stationary longitudinal mode is always less than that for the stationary transverse and the oscillatory transverse modes. Hence the preferred form of disturbance is the stationary longitudinal mode both in the presence and absence of the variable gravity effect. The stability equations for stationary instability (with $\sigma=0$) are thus given by

$$\begin{aligned}&\Lambda g(z)\left(D^2-a^2\right)^2W\\ &+2\Lambda V^2g^3(z)\left(D^2+a^2\right)W\\ &-2\Lambda Vg^2(z)\left(D^2-a^2\right)DW\\ &+Na^2D\phi-R(1+\eta z)a^2\theta\\ &-Da^{-1}g(z)\left(D^2-a^2\right)W-Na^2\theta=0\end{aligned} \quad \text{... (29)}$$

$$\left(D^2-a^2\right)\theta+W=0 \quad \text{... (30)}$$

$$\left(D^2-M_3a^2\right)\phi-D\phi=0 \quad \text{... (31)}$$

The system of equations (29)-(31) can be regarded as an eigenvalue problem in with the different parameters of the problem at hand and can be solved using the Galerkin technique which deals with a large parameter space in an economic manner.

4.0 Results and discussion

The variable viscosity and variable gravity effect on Darcy-Brinkman ferroconvection is investigated. Realistic hydrodynamic boundary conditions and general magnetic boundary conditions are considered. The local thermal equilibrium condition for the fluid and solid matrix is assumed. The critical values associated with stationary instability are computed by means of the higher order Galerkin method. The thermal Rayleigh number R is a function of both magnetic and non-magnetic parameters. The change in critical Rayleigh number R_c with magnetic Rayleigh number N, Brinkman number Λ, inverse Darcy number Da^{-1}, variable viscosity parameter V, variable gravity effect parameter η, non-buoyancy-magnetization parameter M_3 and magnetic susceptibility χ is exhibited. Numerical computations to find the critical Rayleigh number R_c have been carried out for various values of the parameters. The results are presented in Fig.2 through 4.

Fig.1 reveals that the system is most stable when the magnetic field dependent variable viscosity parameter V increases from 0 to 1. This is due to the fact that magnetization of the magnetic fluid is an increasing function of the strength of the magnetic field. Figs.2 and 3 reveal that the system is again more stable with an increase in the porous parameters V and Da^{-1}.

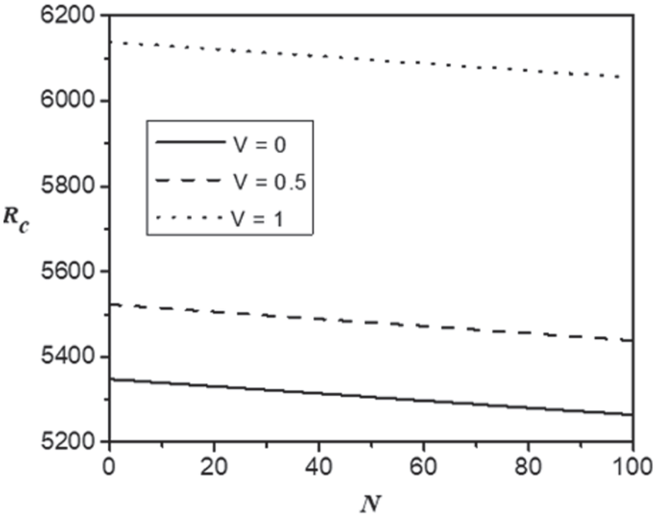

Fig.2: Plot of as a function of N for different values of V

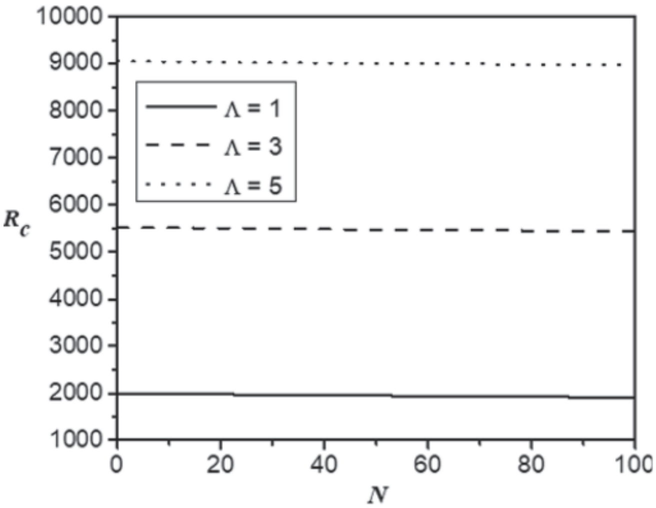

Fig.3: Plot of as a function of N for different values of

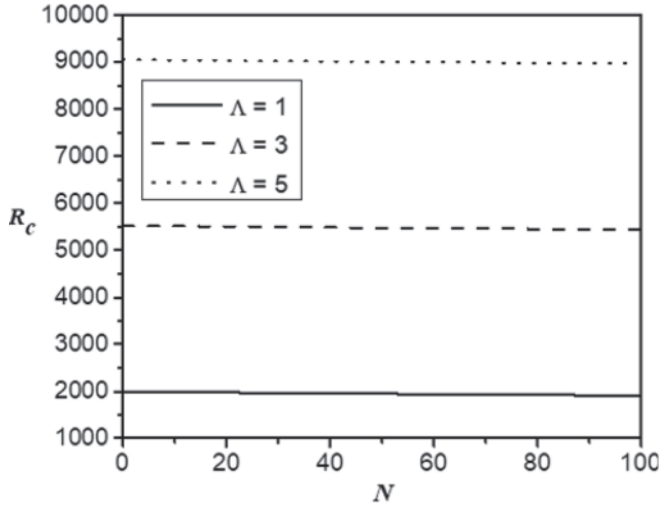

Fig.4: Plot of as a function of N for different values of

The destabilizing influence of the magnetic mechanism is apparent from the Figs.2 through 4. Indeed, the critical Rayleigh number decreases with an increase in the magnetic Rayleigh number N and this augmenting effect of N is more pronounced with respect to the magnetic field dependent variable viscosity parameter V and the inverse Darcy number Da^{-1}. Computations reveal that onset of ferroconvection is advanced when the variable gravity parameter η increases. This is due to the fact that when η increases, the gravity level is lifted up. As a result, there is a decrease in the critical Rayleigh number. Further, both M_3 and χ have negligible influence on the threshold of Darcy-Brinkman ferroconvection with M_3 advancing the onset of ferroconvection and χ inhibiting the ferrconvective instability.

In the absence of the variable gravity, variable viscosity and porous medium, the results agree with those obtained by Finlayson (1970).

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